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Age and Petrology of the Kalaupapa Basalt, Molokai, Hawaii[1]

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ABSTRACT: The post-erosional Kalaupapa Basalt on East Molokai, Hawaii, erupted between 0.34 and 0.57 million years ago to form the Kalaupapa Peninsula. The Kalaupapa Basalt ranges in composition from basanite to lava transitional between alkalic and tholeiitic basalt. Rare-earth and other trace-element abundances suggest that the Kalaupapa Basalt could be generated by 11–17% partial melting of a light-REE-enriched source like that from which the post-erosional lavas of the Honolulu Group on Oahu were generated by 2–11% melting. The $^{87}Sr/^{86}Sr$ ratios of the lavas range from 0.70320 to 0.70332, suggesting that the variation in composition mainly reflects variation in the melting process rather than heterogeneity of sources. The length of the period of volcanic quiescence that preceded eruption of post-erosional lavas in the Hawaiian Islands decreased as volcanism progressed from Kauai toward Kilauea.

THE EDIFICES of Hawaiian volcanoes are constructed of voluminous tholeiitic lava flows, frequently capped by flows of alkalic composition. In addition, many Hawaiian volcanoes have a post-erosional volcanic stage during which lavas of alkalic composition are erupted in small volume. The Honolulu Group on Oahu, the Koloa Volcanics on Kauai, the Kiekie Volcanics on Niihau, the Lahaina Volcanics and Hana Group on Maui, and the Kalaupapa Basalt on East Molokai are examples.[5] The post-erosional stage, by definition, always follows an extended period of volcanic quiescence and erosion. It is unclear whether the length of the quiescent period is similar on each island or varies systematically or randomly. Also, little is known about the detailed petrology of many of these post-erosional volcanic units with the notable exception of the Honolulu Group on Oahu (Jackson and Wright 1970; Lanphere and Dalrymple 1980; Clague and Frey 1982). This paper presents new K–Ar age data, major- and trace-element geochemistry, and Sr-isotopic data of the post-erosional alkalic basalt that forms the Kalaupapa Peninsula on Molokai.

GEOLOGIC SETTING

The island of Molokai is located between the islands of Oahu and Maui in the linear Hawaiian Island chain. Molokai is 78 × 16 km and elongate east-west. It is composed of two coalescing volcanoes, West Molokai Volcano, which rises 421 m above sea level, and the younger East Molokai Volcano, which rises 1515 m above sea level. Stearns and Macdonald (1947) presented a detailed account of the geology of Molokai and the only geologic map of the island (Figure 1). Both volcanoes are capped by alkalic rocks

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[5] The Honolulu Group (formerly the Honolulu Volcanic Series of Stearns 1935; also, formerly the Honolulu Volcanics of Lanphere and Dalrymple 1979), the Koloa Volcanics (formerly the Koloa Volcanic Series of Stearns 1946), the Lahaina Volcanics (formerly the Lahaina Volcanic Series of Stearns and Macdonald 1942), and the Hana Group (formerly the Hana Volcanic Series of Stearns and Macdonald 1942; also, formerly the Hana Formation of Macdonald 1978) are here renamed in order to meet the provisions of articles 9(a) and 9(f) of the Code of Stratigraphic Nomenclature, A.A.P.G., 1970.

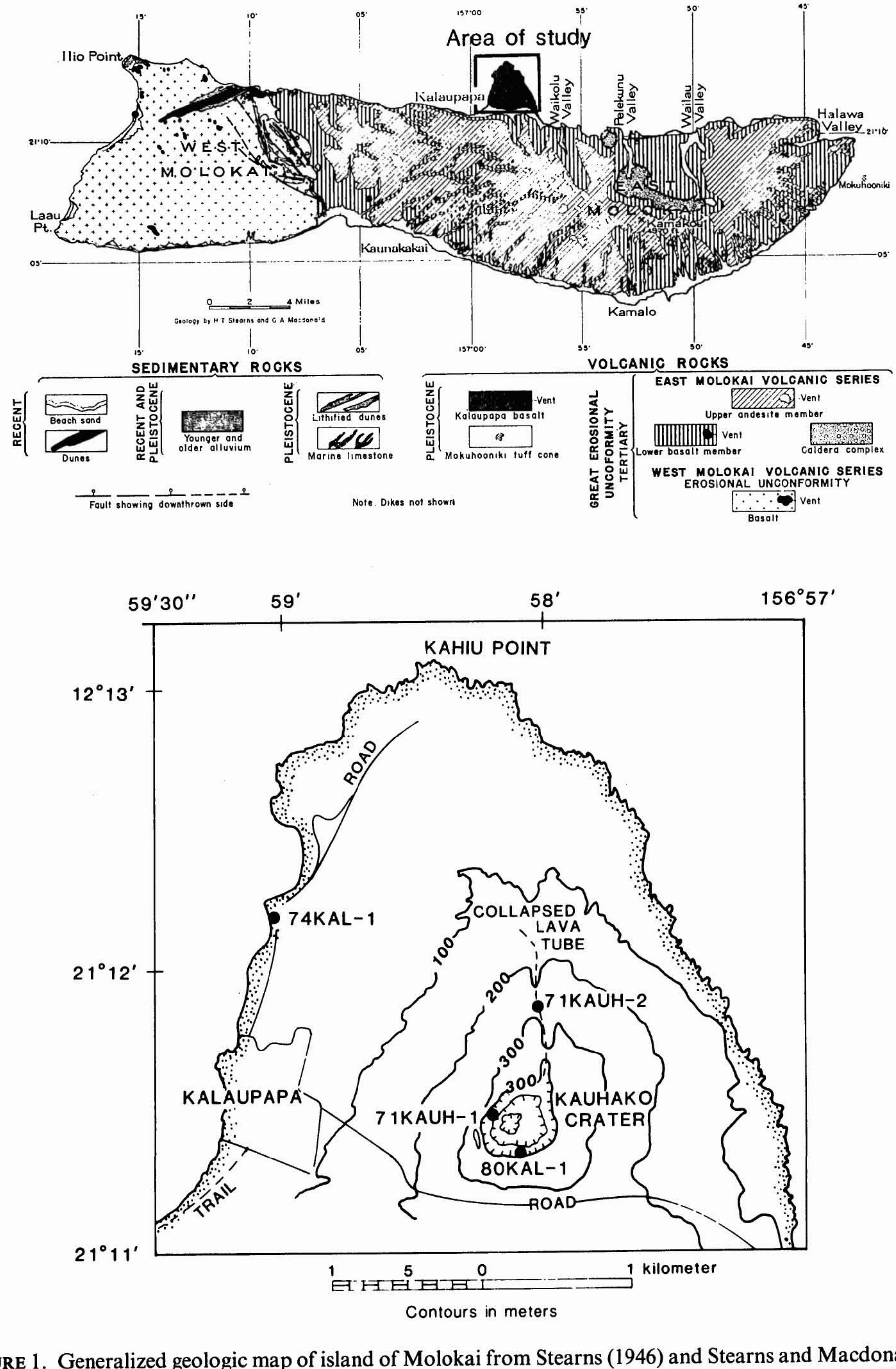

FIGURE 1. Generalized geologic map of island of Molokai from Stearns (1946) and Stearns and Macdonald (1947) showing the Kalaupapa Peninsula on the north-central coast and Mokuhooniki Island off the east coast. The sample locations are shown on the enlarged map of the Kalaupapa Peninsula.

of the post-caldera alkalic stage. On West Molokai Volcano the alkalic eruptive stage comprises only a few flows of hawaiite and alkalic basalt exposed on its southern flank (Macdonald and Abbott 1970). In contrast, East Molokai Volcano has a thick sequence of interbedded transitional and alkalic lavas (Beeson 1976; Clague and Beeson 1980) that is dominated by alkalic lavas near the top of the section.

The post-erosional stage on East Molokai consists of the eruptive products of two vents: one vent formed the Kalaupapa Peninsula on the north coast, and the other formed the now-dissected palagonite tuff cone of Mokuhooniki and Kanaha islands off the east coast of Molokai. The Kalaupapa Peninsula is composed of alkalic olivine basalt that erupted from a small lava shield surmounted by a deep summit crater named Kauhako Crater. A large collapsed lava tube is present on the north side of the shield. The Mokuhooniki lavas have been neither sampled nor dated.

Previous K–Ar work indicates that the alkalic phase of shield building on East Molokai Volcano is about 1.51 to 1.53 million years old (McDougall 1964). The single sample of the underlying tholeiitic unit that has been dated yielded an age of 1.75 ± 0.07 million years (Naughton, Macdonald, and Greenberg 1980). In the same study, Naughton and co-workers published a K–Ar age of 1.24 ± 0.16 million years for a single sample of basalt from the Kalaupapa Peninsula collected in Kauhako Crater. The authors noted that this "surprisingly old age" of the Kalaupapa Basalt implies erosion of the cliffs on north Molokai in less than 500,000 years since the formation of the tholeiitic shield. This age, if correct, indicates about 250,000 years for erosion to form the cliffs following the eruption of the alkalic upper member of the East Molokai Volcanics as dated by McDougall (1964). It is also possible that this scarp was formed by a large landslide.

PETROGRAPHY OF SAMPLES

Samples for this study were collected in 1971 by M. H. Beeson, in 1974 by D. A. Clague, and in 1980 by R. T. Holcomb. Sample 71KAUH-1 is from the west wall and sample 80KAL-1 is from the south wall of Kauhako Crater. Sample 71KAUH-2 is from the collapsed lava tube about 500 m to the north of Kauhako Crater, and sample 74KAL-1 is from a beach outcrop near Kalaemilo point on the west coast of the peninsula about 0.9 km north of the town of Kalaupapa. The two samples from the crater contain 13–16% olivine as the sole phenocryst phase. The olivine encloses rare dark-brown to opaque chromian spinel. The olivine phenocrysts are oxidized in sample 71KAUH-1 but are fresh in 80KAL-1. Sample 71KAUH-2 contains less than 1% plagioclase as microphenocrysts in addition to about 12% olivine phenocrysts. Its groundmass has variable grain sizes with patches that are finer grained and others that are more coarsely crystalline than the bulk of the subophitic groundmass. The coarse-grained portions appear to be segregation vesicles and are characterized by intersertal glass and dark-purple-brown clinopyroxene that is weakly pleochroic. Sample 74KAL-1 is coarser grained and more vesicular than the other samples (16% in vesicles 74KAL-1 and 4–7% in the other samples) and contains 12% plagioclase, 4% clinopyroxene, and 16% olivine phenocrysts. The olivine phenocrysts are rimmed by bright orange iddingsite, and rare groundmass olivine (~3%) is completely altered to iddingsite. Iddingsite after olivine is the only alteration observed. This sample has intergranular to diabasic texture. All the samples meet normal petrographic criteria for suitability for K–Ar dating (Mankinen and Dalrymple 1972).

ANALYTICAL TECHNIQUES

Samples for argon analyses were crushed to −18 to +3.0 mesh. A split of this material was ground to −200 mesh, and two separate splits of this powder were analyzed for K_2O in duplicate (4 measurements total) by flame photometry after lithium metaborate fusion and dilution (Ingamells 1970). Argon analyses were by isotope-dilution mass spectrometry

TABLE 1

POTASSIUM–ARGON AGES AND ANALYTICAL DATA FOR KALAUPAPA PENINSULA OF MOLOKAI, HAWAII

		K_2O*			Argon†					
SAMPLE NO.	MATERIAL	VALUE	S.D.	NO.	Ar-40‡ (mol/g)	Ar-40‡ percent	AGE (m.y.)	S.D. (m.y.)	WEIGHTED MEAN (m.y.)	S.D. (m.y.)
71KAUH-1	Basalt	0.749	0.005	4	3.1954E-13	1.5	0.296	0.044	0.354	0.028
					4.2346E-13	2.2	0.393	0.036		
71KAUH-2	Basalt	0.470	0.007	4	2.1901E-13	2.8	0.324	0.044	0.344	0.031
					2.4753E-13	2.8	0.366	0.046		
80KAL-1	Basalt	0.546	0.007	4	4.078E-13	2.6	0.519	0.049		
					4.081E-13	2.7	0.519	0.049	0.570	0.025
					4.7596E-13	4.0	0.605	0.029		

* K_2O analyses by P. R. Klock.
† Argon analyses by Chen Dao-gong.
‡ Ar-40 indicates radiogenic argon.

using a high purity (>99.9%) ^{38}Ar tracer and using techniques and equipment described by Dalrymple and Lanphere (1969). Argon mass analyses were done on a computerized multiple-collector mass spectrometer with a 22.86-cm radius and 90° sector (Stacey et al. 1981; Sherrill and Dalrymple 1981).

Splits of the same powder used for K_2O analysis were dissolved in HF and $HClO_4$, and Rb and Sr were separated using ion-exchange chromatography. The isotopic composition of Sr was measured on a computer-controlled, 23-cm radius, stigmatic-focusing, 90°-sector mass spectrometer utilizing a double-filament source and a double ion collector.

The measured ^{86}Sr/^{88}Sr ratios were normalized to a value of 0.1194, and a mass fractionation correction was applied to the measured ^{87}Sr/^{86}Sr ratios using a modified power law. The normalized ratios were then adjusted to a value of 0.71014 for the NBS 987 $SrCO_3$ standard.

The major- and trace-element analyses were performed in the Analytical Laboratories of the U.S. Geological Survey, except for the X-ray fluorescence major-element analyses of samples 71KAUH-1 and 80-KAL-1, which were performed at the University of Massachusetts. The major-element analysis of sample 71KAUH-2 was a classical wet-chemical analysis while that of 74KAL-1 was by X-ray fluorescence. The trace elements were analyzed by atomic absorption spectrometry for Li, V, Ni, and Cu; by X-ray fluorescence for Rb, Sr, Y, Zr, Nb, and Ba; by instrumental neutron activation for Sc, Cr, Co, Zn, Hf, Ta, Th, and the rare earth elements; and by delayed neutron activation for U. The analysts are listed in the tables.

RESULTS

Potassium–Argon Data

The K–Ar data are listed in Table 1. Radiogenic ^{40}Ar was less than 5% in all of the samples. The ^{40}Ar in two measurements of sample 74KAL-1 was less than 0.5% radiogenic, so no age was calculated. The other three samples yielded ages ranging from 0.34 to 0.57 million years. These ages are far younger than the 1.24 ± 0.16 million-year age reported by Naughton, Macdonald, and Greenberg (1980), although the reasons for the discrepancy are unclear. From the new age data, we conclude that the Kalaupapa Peninsula was constructed of alkali olivine basalt flows between 0.344 ± 0.032 and 0.570 ± 0.025 million years ago. These data indicate that the period of volcanic quiescence and erosion between the alkalic stage and the eruption of the post-erosional Kalaupapa Basalt lasted about 1 million years.

TABLE 2

MAJOR-ELEMENT DATA: KALAUPAPA BASALT

	71KAUH-1*	71KAUH-2†	74KAL-1‡	80KAL-1*	MOE 2§
SiO_2	43.7	45.59	45.8	45.4	43.02
Al_2O_3	12.2	12.86	13.7	13.4	11.82
Fe_2O_3	14.9	1.92	3.68	13.6	5.26
FeO	—	10.73	9.11	—	9.19
MgO	11.9	13.06	10.4	10.3	13.76
CaO	10.8	10.32	10.9	11.2	10.37
Na_2O	2.57	2.41	2.29	2.77	2.74
K_2O	0.74	0.42	0.27	0.55	0.74
H_2O^+	—	0.24	0.57	—	0.88
H_2O^-	—	0.20	0.61	—	0.21
TiO_2	2.43	1.73	1.59	1.97	2.17
P_2O_5	0.35	0.21	0.20	0.26	0.33
MnO	0.18	0.18	0.19	0.18	0.16
CO_2	—	0.02	0.19	—	—
S	—	0.03	—	—	—
Subtotal	99.8	99.92	99.50	99.6	100.65
Less 0	—	0.02	—	—	—
Total	99.8	99.90	99.50	99.6	100.65

* Major-element X-ray fluorescence analysis by M. Rhodes, Univ. of Massachusetts, Amherst.
† Wet chemical analysis by Edythe Engleman; Project Leader, D. Norton.
‡ Major-element X-ray fluorescence analysis by J. S. Wahlberg, J. Taggart, and J. Baker; partial chemistry for H_2O^+, H_2O^-, FeO, and CO_2 by M. Taylor.
§ Analysis from Naughton, Macdonald, and Greenberg (1980).

Geochemistry

Major-element analyses of our four samples are given in Table 2 with an additional analysis from Naughton, Macdonald, and Greenberg (1980). The samples can be classified as alkali olivine basalt, although the sample analyzed by Naughton and coauthors (1980) has 7.1% normative nepheline and approaches a basanite in composition. Sample 74KAL-1 falls very near the tholeiitic field on an alkali-silica diagram (Figure 2) and actually has 5.7% hypersthene in the C.I.P.W. norm; it could therefore be classified as a transitional basalt. The five samples have high $Mg/Mg + Fe^{2+}$ ratios (0.67–0.73) and are close to being primary mantle partial melts.

The range in normative mineralogy is reflected in large variations in Na_2O, K_2O, TiO_2, and P_2O_5 contents. These variations cannot be a result of shallow fractionation alone; they require that the Kalaupapa magmas either were generated by variable degrees of partial melting of a single source, or were generated from compositionally distinct sources, or both.

Isotopic and trace-element data are particularly useful in assessing the alternative models for the generation of these lavas. Trace-element data for samples 74KAL-1 and 71KAUH-2 are given in Table 3, and $^{87}Sr/^{86}Sr$ ratios for all four samples are given in Table 4. The samples have similar $^{87}Sr/^{86}Sr$ ratios (range 0.70320–0.70332), suggesting that the variation in lava composition mainly reflects variation in the melting process rather than the composition of the mantle source. Representative microprobe mineral analyses are presented in Table 5.

The normalized rare-earth patterns of samples 71KAUH-2 and 74KAL-1 are shown in Figure 3. These samples have nearly identical rare-earth and P_2O_5 abundances, which suggests that they were generated by similar degrees of partial melting; yet they have distinct abundances of Na_2O, K_2O, and TiO_2. These differences suggest that partial melting to form these two rocks left different proportions

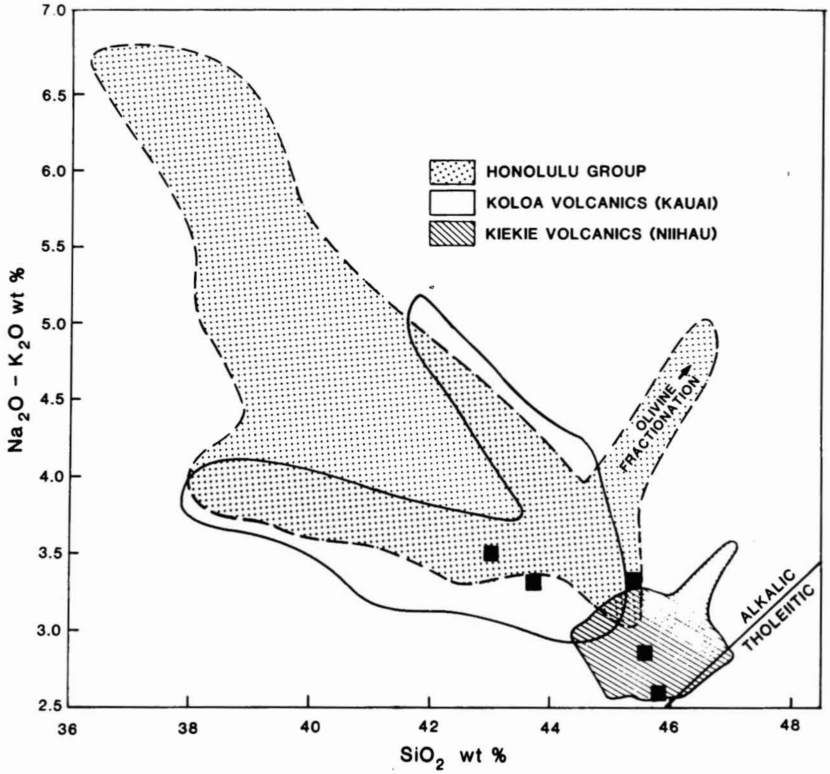

FIGURE 2. Alkali-silica diagram showing the fields for post-erosional lavas from the Honolulu Group on Oahu (Clague and Frey 1982), the Koloa Volcanics on Kauai (D. A. Clague, unpub. data), the Kiekie Volcanics on Niihau (D. A. Clague, M. H. Beeson, G. B. Dalrymple, and E. D. Jackson, unpub. data) and the analyzed samples from the Kalaupapa Basalt on East Molokai (plotted as solid squares). The line separating the fields of Hawaiian alkalic and tholeiitic lavas is from Macdonald and Katsura (1964). The Kalaupapa Basalt samples range in composition from basanite to lava transitional in composition between alkalic and tholeiitic basalt.

of phases that retain K_2O, TiO_2, and Na_2O in the mantle residuum. The Kalaupapa Basalt samples have Sr isotopic ratios similar to those of the Honolulu Group (average 0.70332 ± 0.00004, Lanphere and Dalrymple 1980) and also have trace-element ratios similar to those of alkali basalt and basanite in the Honolulu Group (Clague and Frey 1982). The $^{87}Sr/^{86}Sr$ ratios of the Kalaupapa Basalt samples are significantly lower than those of two samples of tholeiite from East Molokai Volcano which are about 0.7037 (Lanphere, Dalrymple, and Clague 1980). A similar pattern of Sr isotopic composition is found between the Honolulu Group and tholeiite of the Koolau Volcanics (Lanphere and Dalrymple 1980). The Kalaupapa Basalt could be generated by 11–17% partial melting of a light-REE-enriched source like that from which those of the Honolulu Group were generated by 2–11% melting. Like the Honolulu Group lavas, the Kalaupapa Basalt samples are depleted in TiO_2, Zr, Hf, Y, Nb, and Ta, suggesting that these elements are retained in a residual mantle phase, perhaps ilmenite, during partial melting.

DISCUSSION

Potassium–argon ages of 0.34 to 0.57 million years reported here for the post-erosional Kalaupapa Basalt leave about 1 million years of volcanic quiescence during which the spec-

TABLE 3

TRACE-ELEMENT DATA: KALAUPAPA BASALT

	71KAUH-2	74KAL-1
Li	—	11
Sc	24	26
V	—	—
Cr	581	572
Co	69	71
Ni	—	—
Cu	—	120
Zn	100	115
Rb	—	40
Sr	—	319
Y	—	18
Zr	—	69
Nb	—	16
Ba	—	160
La	13	14
Ce	26.5	30
Nd	18.5	16
Sm	3.7	3.7
Eu	1.29	1.25
Gd	4.1	3.3
Tb	0.45	0.60
Ho	0.38	0.4
Yb	1.45	1.7
Lu	0.21	0.22
Hf	2.25	1.9
Ta	1.16	4.2
Th	1.16	1.3
U	—	0.28

TABLE 4

SR ISOTOPIC COMPOSITION* OF THE KALAUPAPA BASALT

	$^{87}Sr/^{86}Sr$	1σ
71KAUH-1	0.703207	±0.000024
	0.703234	±0.000013
71KAUH-2	0.703323	±0.000023
74KAL-1	0.703203	±0.000007
80KAL-1	0.703228	±0.000014
	0.703219	±0.000024

*Sr analyses by R. Murnane.

tacular cliffs on the north coast of Molokai were formed.

The length of the period of volcanic quiescence that precedes eruption of the post-erosional lavas in the Hawaiian Islands is not constant. Figure 4 shows the age and length of the period of quiescence for volcanoes that have post-erosional lavas, including Haleakala, Maui; West Maui; East Molokai; Kauai; and Niihau. This plot shows that the duration of the quiescent period between the shield-building and post-erosional stages became shorter as the volcanism progressed from Kauai to Haleakala (closer to Kilauea). At Haleakala, the undated post-erosional Hana Group can post-date the alkalic stage Kula Formation by no more than 400,000 years, the age of the Kula Formation.

Jackson and Wright (1970), using tide-gauge data from Moore (1971), suggested that generation of the post-erosional Honolulu Group might be due to uplift as Oahu passed over the Hawaiian Arch. They argued that the Hawaiian Arch, an isostatic response to volcanic loading on the oceanic crust, followed the active volcanic center by several hundred kilometers and several million years. This simple model does not explain the data shown in Figure 4. Although it is possible that a more sophisticated model of lithospheric flexure due to volcanic loading of all nearby volcanoes could fit the age data, it is difficult to point to a change from subsidence to uplift as the energy source for magma generation for volcanoes younger than Koolau Volcano because these volcanoes are still subsiding rapidly. We suggest that a new mechanism must be sought to explain the occurrence of Hawaiian post-erosional volcanism.

The Kalaupapa Peninsula is made of a range of basalt compositions varying from basanite to lava transitional in composition between alkalic and tholeiitic basalt. These diverse lavas all apparently erupted from a single vent. Each vent of the Honolulu Group on Oahu generally erupted only one type of basalt, although a few vents, such as Salt Lake Crater, erupted lava with a range of compositions. The similarity of the Kalaupapa Basalt in Sr-isotopic composition and trace-element ratios to those of the Honolulu Group (Lanphere and Dalrymple 1980; Clague and Frey 1982) is striking and suggests that the Kalaupapa Basalt was derived from a mantle source nearly identical to that of the Honolulu Group.

TABLE 5

MICROPROBE MINERAL COMPOSITIONS: KALAUPAPA BASALT

	Cr-SPINEL			TITANOMAGNETITE				OLIVINE		PLAGIOCLASE		
	1	2	3	4	5	6		7		8	9	10
Al_2O_3	27.8	27.1	25.2	1.09	0.99	1.14	SiO_2	—	SiO_2	49.6	49.4	49.2
MgO	10.8	12.9	13.2	0.49	0.73	0.56	FeO	20.3	Al_2O_3	31.4	31.0	31.0
TiO_2	1.40	1.18	1.11	27.8	27.0	27.3	MgO	39.9	Fe_2O_3	0.47	0.61	0.60
MnO	0.20	0.19	0.17	0.59	0.65	0.58	CaO	—	CaO	14.1	14.6	13.8
Cr_2O_3	28.6	27.9	32.5	0.03	0.03	0.03	MnO	—	Na_2O	3.60	3.36	3.78
FeO	29.65	28.8	25.8	64.7	66.5	65.5	NiO		K_2O	0.10	0.09	0.11
Total	98.45	98.1	98.0	94.7	95.9	95.1	Total	—	Total	99.3	99.1	98.5
							Fo	78	AN	68	70	66

Legend for Analyses

1. 74KAL-1, Cr-spinel in olivine phenocryst
2. 74KAL-1, Cr-spinel in olivine phenocryst
3. 71KAUH-2, Cr-spinel in olivine phenocryst
4. 74KAL-1, groundmass crystal
5. 71KAUH-2, groundmass crystal
6. 71KAUH-2, groundmass crystal
7. 74KAL-1, phenocryst core
8. 74KAL-1, microphenocryst
9. 71KAUH-2, microphenocryst
10. 71KAUH-2, microphenocryst

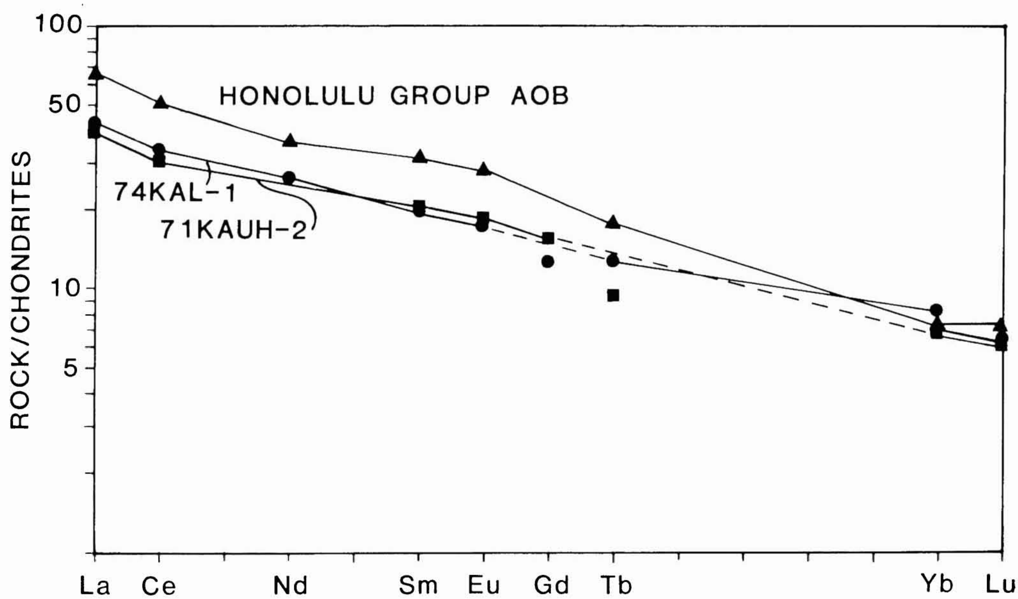

FIGURE 3. Chondrite-normalized rare-earth element diagram showing two samples of the Kalaupapa Basalt and, for comparison, an average of the four samples of basanite and alkalic basalt from the Honolulu Group having the lowest rare-earth contents (Clague and Frey 1982). If the Honolulu Group lavas shown are generated by 11% melting as proposed by Clague and Frey, then the Kalaupapa Basalt samples shown are generated by about 17% partial melting. These estimates assume that the source compositions are the same for the Honolulu Group and the Kalaupapa Basalt. See text for more detailed discussion.

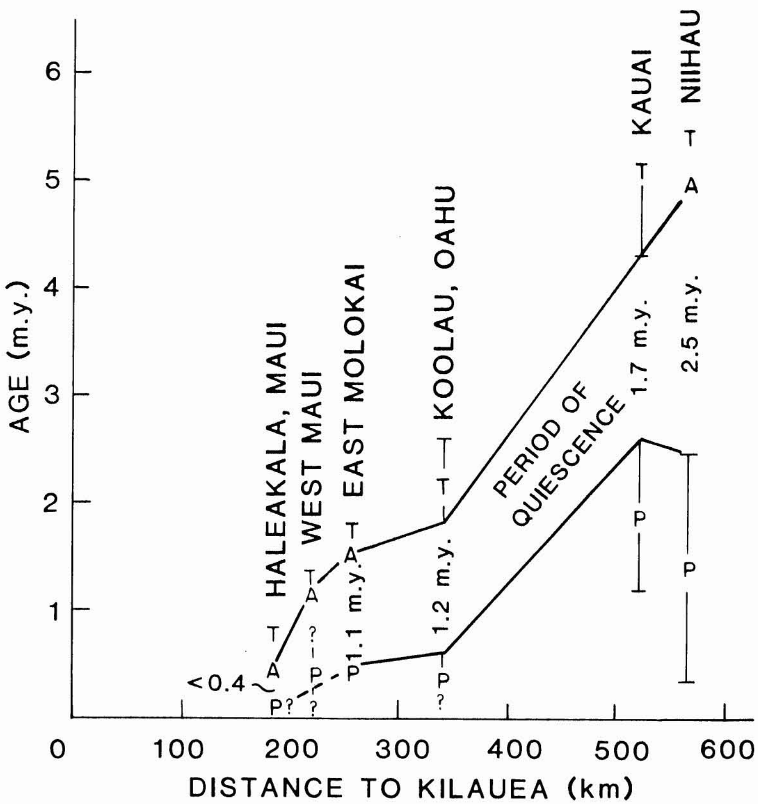

FIGURE 4. Ages of tholeiitic (T), alkalic (A), and post-erosional (P) stages for the Hawaiian Islands that have both age data and post-erosional lavas as a function of distance to Kilauea. Sources of data: Niihau (G. B. Dalrymple, unpub. data), Kauai (McDougall 1979 for tholeiitic stage, G. B. Dalrymple and D. A. Clague unpub. data for the post-erosional Koloa Volcanics), Koolau (Doell and Dalrymple 1973 for tholeiitic stage, Lanphere and Dalrymple 1980 for the post-erosional Honolulu Group), E. Molokai (Naughton, Macdonald, and Greenberg 1980 for tholeiitic stage, McDougall 1964 for alkalic stage, and this study for post-erosional stage), W. Maui (McDougall 1964 for tholeiitic and alkalic stages, no reliable data for post-erosional Lahaina Volcanics), and Haleakala (Naughton and co-authors 1980 for tholeiitic stage, McDougall 1964 for alkalic stage, no data for the post-erosional Hana Group). The duration of the quiescent period decreases systematically from 2.5 million years on Niihau to <0.4 million years on Haleakala.

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